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AERODYNAMIC FOCUSING OF LARGE PARTICLES

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GOAL - Develop a Method to Focus a Beam of Large (>10 μm) Particles

REQUIREMENTS:

- **Direct a Stream of Large (> 10 μm) Particles for Fabrication and Measurement Applications**
- **Increase Particle Flux / Reduce Particle Stream Area**
- **Operation at Nominally Atmospheric Conditions**
- **Operation Preferably With Air or Nitrogen**

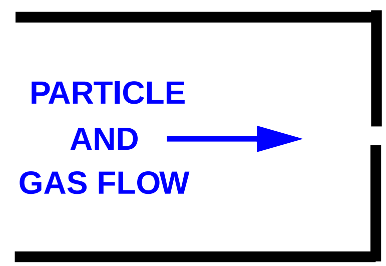
RESULT: *Large particle Aerodynamic Focusing* - A Set of Design Guidelines Specifying the Operational Range of Aerodynamic Lenses for Focusing Large Particles

Aerodynamic Focusing of Large Particles
BACKGROUND

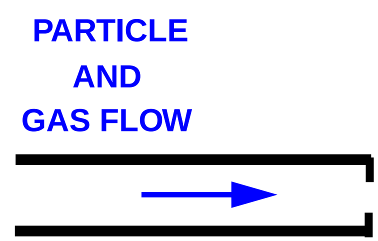
Generation of Particle Beams and Aerodynamic Focusing of Particles is Established in the Literature*

Two Basic Designs for Axial Flow

- **Initial gas and particle velocity are small compared to the gas velocity in the orifice or nozzle performing the focusing. The flow looks like flow from a large volume into a sink.**



- **Initial gas and particle velocities are not small compared to the orifice or nozzle gas velocity. Flow looks like tube flow passing through an axial constriction**



* Israel, G. W. and Friedlander, S. K., (1967), Dahneke, B.E., (1978), Fernandez de la Mora, et al., (1989), Fernandez de la Mora, J. and Riesco-Chueca, P., (1988), Fuerstenau, S., Gomez, A., and Fernandez de la Mora, J., (1994), Rao, N., et al., (1996), Liu, P., et al., (1995a), Liu, P., et al., (1995b).

Focusing Has Been Demonstrated

- Particles Smaller Than a Few Micrometers
- Pressures at Atmospheric and Less
- Focusing Depends on Particle Stokes Number
- Increased Focusing Can Be Obtained With Multiple Lens Systems

Second Type of Focusing System Selected for This Work

Additional Considerations for Focusing Larger Particles

- Gravitational Settling
- Particle Impaction on the Upstream Side of the Focusing Element
- Flow Attachment Considerations Bring in Reynolds Number Dependence
- Concentration Effects

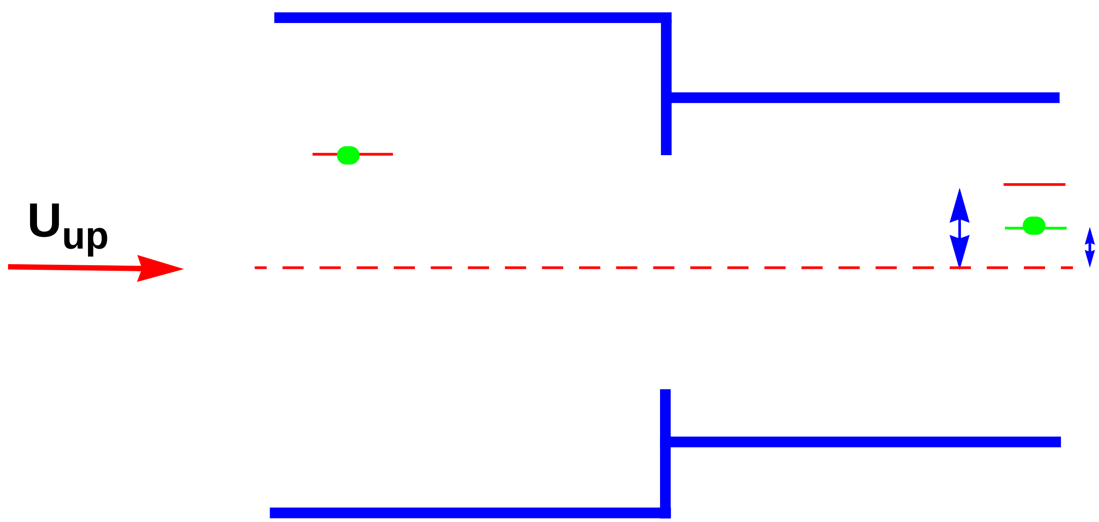
Aerodynamic Focusing of Large Particles
STOKES NUMBER

Particle Stokes Number

- $Stk = \tau U_{up} / d$

Concentration Factor

- Radius of initial Streamline Divided By Radius of Final Streamline
- Square of Concentration Factor Gives Enrichment



Aerodynamic Focusing of Large Particles
CALCULATED CONCENTRATION FACTORS

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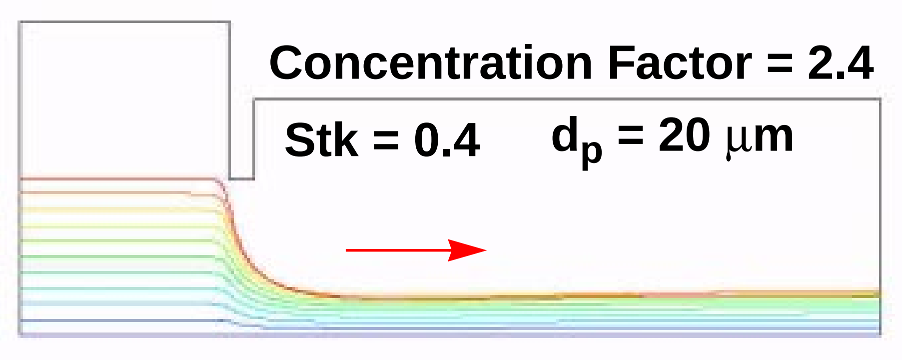
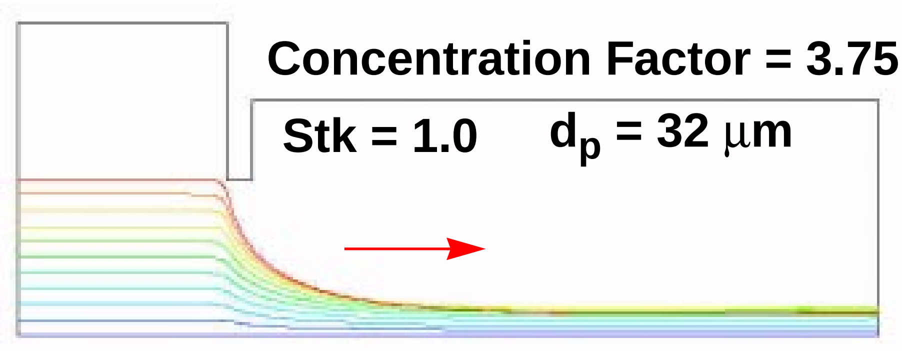
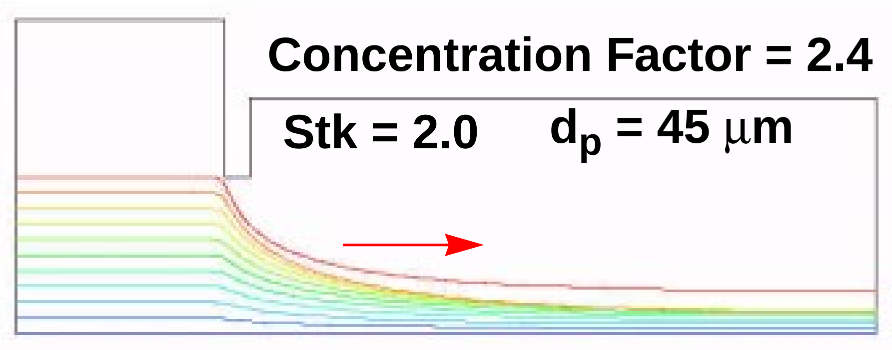
Conditions

- Flow Directed Downward
- Gravity Included in Calculation
- P = 1 atm
- T = 295 K
- U = 86.5 cm/sec
- Re = 300
- D_{up} = 0.533 cm
- d = 0.267 cm
- D_{dn} = 0.40 cm







Aerodynamic Focusing of Large Particles
GRAVITATIONAL SETTLING

The Particle Gravitational Settling Velocity Can Be a Significant Fraction of the Gas Flow Velocity

- **Select Flow Velocity To Be At Least 5, Preferably 10 times the Particle Settling Velocity**
  - **This Acts to Increase Reynolds Numbers in the Tube**
- **Operate Vertically So That Particles Settle in the Axial Direction**
  - **Vertical Operation May Have to Deal With Saffman Lift Forces:**
    - **Toward the Wall For Downward Flow**
    - **Toward the Center For Upward Flow**

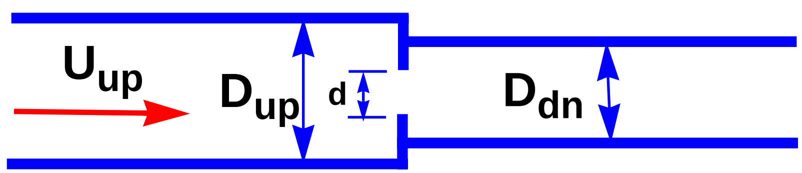
TUBE REYNOLDS NUMBER

In Multiple Lens Systems

- **Flow Exiting a Lens as a Jet Must Re-Attach to the Tube Wall for the Next Lens to Function**
- **Without Re-Attachment, Flow Recirculation Is Established Between the Lenses In the Annular Region Around a Flowing Central Core**
- **Particles Continue Through Core Region Without Focusing**
- **Correlation for Re-Attachment Length**
    - **Linear With Reynolds Number**
    - **Sensitive to Expansion Ratio**

Stepped Approach

- **Making Subsequent Tube Diameters Smaller Reduces Re-Attachment Length**



Large Particles Can Impact on the Upstream Face of the Aerodynamic Lens

Condition for Impaction In Laminar Flow

- Stk > 0.213
- Gravitational Settling in Downward Flow May Cause Impaction at Lower Stk

Use of Sheath Flow Can Eliminate Impaction

- Necessary Only for First Lens
- With Focusing, Particles Aligned for Subsequent Lens

Higher Particle Concentrations May Be Desirable for Fabrication Applications - High Mass Flux

Aerodynamic Focusing May Degrade With Higher Particle Loading

- **Inter-Particle Distances May Violate Single Particle - Gas Interaction Assumptions**
- **High Concentration Aerosols Can Behave as a Separate Fluid with a Higher Density When Interacting With Clean Gas - Cloud Effects**
- **Particle - Particle Collisions Could De-Focus the Particle Stream**

Experiments Conducted With High Particle Loading

Experimental Demonstration of Aerodynamic Focusing of Large Particles

- 3 Stage System
  - Tube Diameters = 9.5 mm, 7.6 mm, 6.1 mm
  - Orifice Diameter = 0.5 Upstream Tube Diameter
  - Final orifice = 3 mm
- 3.7 ALMP He Total FLow (Minimal Sheath Gas Flow)
- 15 μm Aluminum Particles
  - High Loading
- Final Aerosol Beam Diameter = 1 mm

Aerodynamic Focusing of Large Particles
CONCLUSIONS

- **Aerodynamic Focusing Can Be Accomplished With Large (>10 μm) Particles**
- **Inertial Impaction of Particles on Upstream Face of Focusing Element Can Be Eliminated With Sheath Gas**
- **Gravitational Settling of Particles Must Be Considered**
    - **Keep Gas Velocity "Large" Compared to Particle Settling Velocity**
    - **Operate Focusing System With Flow in the Vertical Direction**
- **Flow Re-Attachment Necessary in Multiple-Stage Systems**
    - **Keep Reynolds Numbers Low**
    - **Use Stepped Stages With Decreasing Tube Diameters**
- **Future Work**
    - **Further Experimental Investigation**
    - **Investigate Particle Loading Effects**